Metallogenesis and Tectonics of Northeast Asia
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Chapter 2

Methodology of a Combined Regional Metallogenic and Tectonic Analysis for Northeast Asia

By Warren J. Nokleberg[1], Thomas K. Bundtzen[2], Kenneth M. Dawson[3], Roman A. Eremin[4], Nikolai A. Goryachev[4], Alexander I. Khanchuk[5], James W. H. Monger[3], Alexander A. Obolenskiy[6], Leonid M. Parfenov[7], Andrei V. Prokopiev[7], Vladimir V. Ratkin[5], Sergey M. Rodionov[8], and Vladimir I. Shpikerman[4]

Introduction

The compilation, synthesis, description, and interpretation of metallogenesis and tectonics of major regions, such as Northeast Asia (eastern Russia, Mongolia, northern China, South Korea, and Japan) and the Circum-North Pacific (the Russian Far East, Alaska, and the Canadian Cordillera) require a complex methodology. The key goal for metallogenic and tectonic analysis is to define, characterize, and interpret the origin and evolution of mineralizing systems. To achieve this goal, a methodology is needed for combined regional metallogenic and tectonic analysis. The methodology, as developed in major international collaborative mineral resource studies led by the U.S. Geological Survey for the Circum-North Pacific and Northeast Asia, consists of the following steps: (1) definition of key terms; (2) compilation of a regional geologic base map that can be interpreted according to modern tectonic concepts and definitions; (3) interpretation of tectonic environments that formed the major geologic units and structures that control the origin and distribution of metallogenic belts; (4) description of significant mineral deposits (database) that enable the determination of mineral-deposit models, the relations of deposits to host rocks, and tectonic origins; (5) synthesis of mineral-deposit models that characterize the known deposits and inferred undiscovered deposits of the region; (6) compilation of a series of metallogenic belt maps on the regional geologic base map; and (7) synthesis and interpretation of a metallogenic-tectonic model.

This chapter presents an overview of the methodology for regional metallogenic and tectonic analysis, provides a theoretical example of this type of analysis, and describes an example for the Middle Jurassic through Early Cretaceous of Northeast Asia. The major sections of this chapter are: (1) definitions, compilations, and syntheses needed for a combined metallogenic and tectonic analysis; (2) a theoretical example of metallogenic and tectonic analysis; (3) description of a theoretical example of synthesizing a metallogenic-tectonic model; (4) example of a compilation of a regional-geologic base map; (5) a discussion of interpreting tectonic environments; (6) a discussion of compiling descriptions of significant mineral deposits and of synthesizing mineral-deposit models; (7) an example of compilation of a metallogenic belt map; (8) an example of a combined metallogenic-tectonic model; and (9) a description of the benefits of synthesizing a combined regional metallogenic-tectonic model.

A major goal of this chapter is to demonstrate that the methodology of regional metallogenic and tectonic analysis is a useful theoretical tool for defining, characterizing, and interpreting the origin and evolution of mineralizing systems throughout geological space and time. This methodology eliminates past problems that have limited some metallogenic and tectonic analyses, including (1) concentration of some metallogenic studies on local features of mineral deposits and districts without an understanding of their regional setting; (2) lack of integration of regional studies of host rocks, structures, and tectonic origins with respect to suites of mineral deposits; and (3) in some cases, application of a stabilistic tectonic philosophy.

[1] U.S. Geological Survey, Menlo Park, Calif.

[2] Alaska Division of Geological and Geophysical Surveys, Fairbanks.

[3] Geological Survey of Canada, Vancouver.

[4] Russian Academy of Sciences, Magadan.

[5] Russian Academy of Sciences, Vladivostok.

[6] Russian Academy of Sciences, Novosibirsk.

[7] Russian Academy of Sciences, Yakutsk.

[8] Russian Academy of Sciences, Khabarovsk.

The methodology described in this chapter was developed for the international collaborative studies on the mineral resources, metallogenesis, and tectonics of Northeast Asia and the Circum-North Pacific (Russian Far East, Alaska, and the Canadian Cordillera) that were led by the U.S. Geological Survey. These studies have produced two broad types of publications. One type is a series of regional geologic, mineral deposit, and metallogenic-belt maps and companion descriptions for the regions, for example, Nokleberg and others (1998, 2004), Obolenskiy and others (2003, 2004), Parfenov and others (2003, 2004a,b), Nokleberg and others (2004), Rodionov and others (2004), and Naumova and others (2006). The other type of publication is a suite of metallogenic and tectonic analyses of these same regions. Major examples of this type are Scotese and others (2001), Nokleberg and others (2000, 2004, 2005), Rodionov and others (2004), and Naumova and others (2006). A summary of the major products of this project are posted on the World Wide Web at URL: http://pubs.usgs.gov/of/2006/1150/PROJMAT/RFE-Ak-Can_Cord_Proj_Pamph.doc and are described in appendix A.

Relatively few combined metallogenic and tectonic analyses for large regions have been published since the 1980s. Most studies on this theme were focused on relatively smaller districts, such as that of the Maniwaki-Gracefield district in southwestern Quebec by Gauthier and Brown (1986). The major example of a regional metallogenic and tectonic analysis is that for the Circum-North Pacific (Russian Far East, Alaska, and the Canadian Cordillera) (Nokleberg and others, 1997a,b,c, 1998, 2000, 2005).

Key Terms Used In Metallogenic and Tectonic Analysis

Key terms used in the compilation, synthesis, description, and interpretation of metallogenic belts in relation to mineral deposits, metallogeny, and tectonics (Nokleberg and others, 2000, 2005) are as follows.

Accretion. Tectonic juxtaposition of terranes to a craton or cratonal margin. Accretion of terranes to one another or to a cratonal margin also produces a major change in the tectonic evolution of terranes and cratonal margins.

Amalgamation. Tectonic juxtaposition of two or more terranes before accretion to a craton or continental margin.

Composite terrane. An aggregate of terranes that is interpreted to share either a similar stratigraphic affinity or a common geologic history after accretion. An approximate synonym is *superterrane.*

Continental-margin arc terrane. Fragment of an igneous belt of coeval plutonic and (or) volcanic rocks and associated sedimentary rocks that formed above a subduction zone dipping beneath a continent. Either has or inferred to possess a sialic basement.

Craton. Chiefly regionally metamorphosed and deformed shield assemblages of Archean, Paleoproterozoic, and (or) Mesoproterozoic sedimentary, volcanic, and plutonic rocks and overlying platform successions of Paleoproterozoic, Paleozoic, and, locally, Mesozoic and Cenozoic sedimentary and lesser volcanic rocks.

Cratonal margin. Chiefly Neoproterozoic through Jurassic sedimentary rocks deposited on a continental shelf or slope. Consists mainly of platform successions. Locally has or may have had an Archean, Paleoproterozoic, and (or) Mesoproterozoic cratonal basement.

Cratonal terrane. Fragment of a craton.

Island-arc system. An island-arc terrane and tectonically linked subduction zone terranes..

Island-arc terrane. Fragment of an igneous belt of plutonic rocks and (or) coeval volcanic rocks, and associated sedimentary rocks that formed above an oceanic subduction zone. May possess a simatic basement.

Metallogenic belt. A geologic unit (area) that either contains or is favorable for containing a group of coeval and genetically-related, significant lode and (or) placer deposits. A metallogenic belt has the following characteristics: (1) is favorable for containing known or inferred mineral deposits of specific type or types; (2) may be irregular in shape and variable in size; (3) need not contain known deposits; and (4) is based on a geologic map as the primary source of information for delineation of areas that are favorable for specific deposit models. An essential part of the definition is that a belt is the geologically-favorable area for a group of coeval and genetically-related mineral-deposit models. This definition provides a predictive character for undiscovered deposits in each belt.

Metamorphic terrane. Fragment of a highly metamorphosed or deformed assemblage of sedimentary, volcanic, or plutonic rocks that cannot be assigned to a single tectonic environment because the original stratigraphy and structure are obscured. May include structural mélange that contains fragments of two or more terranes.

Mine. A site where valuable minerals or rocks have been extracted.

Mineral deposit. A site with concentrations of potentially valuable minerals for which grade and tonnage estimates have been made. Also used as a general term for any mineral occurrence or prospect.

Mineral occurrence. A site of potentially valuable minerals on which no visible exploration has occurred, or for which no grade and tonnage estimates have been made.

Oceanic crust, seamount, and ophiolite terrane. Fragment of part or all of a suite of deep-marine sedimentary rocks, pillow basalt, gabbro, and ultramafic rocks (former eugeosynclinal suite) that are interpreted as oceanic crustal sedimentary and volcanic rocks and upper mantle. Includes both inferred offshore oceanic and marginal ocean-basin rocks, minor arc-derived volcaniclastic rocks, and major marine volcanic accumulations formed at a hot spot, in a fracture zone, or along a spreading axis.

Overlap assemblage. A post accretionary unit of sedimentary or igneous rocks deposited on or intruded into two or more adjacent terranes.

Passive continental-margin terrane. Fragment of a cratonal margin.

Prospect. A site of potentially valuable minerals where excavation has occurred.

Significant mineral deposit. A mine, mineral deposit, prospect, or occurrence that is judged as being important for the metallogenesis of a geographic region.

Subduction-zone terrane. Fragment of a mildly to intensely deformed complex consisting of varying amounts of turbidite deposits, continental-margin rocks, oceanic crust and overlying units, and (or) oceanic mantle. Geologic units are interpreted to have formed during tectonic juxtaposition in a zone of major thrusting (subduction) of one lithospheric plate beneath another, generally along the margin of a continent or an island-arc terrane. May include large fault-bounded fragments with a coherent stratigraphy. Many subduction-zone terranes contain fragments of oceanic crust and associated rocks that exhibit a complex structural history in a major thrust zone, and possess blueschist-facies metamorphic assemblages. An approximate synonym is *accretionary-wedge terrane.*

Superterrane. An aggregate of terranes that is interpreted to share either a similar stratigraphic affinity or a common geologic history after accretion. An approximate synonym is *composite terrane*.

Tectonic Collage. A series of linear island-arc terranes or continental-margin arcs and tectonically-linked (companion) accretionary wedge (subduction) zones and(or) forearc and backarc basins that formed during a major tectonic event in a relatively narrow geologic timespan. Some collages may consist of fragments of cratonal margin and cratonal terranes that were amalgamated before accretion to a continent. The ages of collages with subduction-zone terranes are based on the time of active formation of the subduction zone, rather than the ages of rock units that compose to a companion subduction zone which was adjacent to and underthrust the arc.

Tectonostratigraphic terrane (terrane). A fault-bounded geologic entity or fragment characterized by a distinctive geologic history which differs markedly from that of adjacent terranes (Jones and others, 1983; Howell and others, 1985).

Turbidite-basin terrane. Fragment of a basin filled with deep-marine clastic deposits in either an orogenic forearc or backarc setting. May include continental-slope and continental-rise turbidite deposits, and submarine-fan turbidite deposits on oceanic crust. May also include minor epiclastic and volcaniclastic rocks.

Theoretical Example of Metallogenic and Tectonic analysis

A theoretical example of metallogenic and tectonic analysis is illustrated in figure 1 (from Nokleberg and others, 1998) which shows a schematic map that portrays a suite of metallogenic belts that are hosted in several geologic units including cratons, terranes, and overlap assemblages, or along major faults between terranes (fig. 1*A*), along with a series of stratigraphic columns for the geologic units (fig. 1*B*).

An orogenic belt map (fig. 1*A*), which is modeled after the major geodynamic units in Northeast Asia, cratons A and B are simplified portrayals of the North Asian craton and cratonal margin and the Sino-Korean craton, respectively. The various terranes and postaccretionary overlap assemblages on figure 1*A* the major faults cutting the terranes and overlap assemblages between the cratons and are simplified portrayals of those between the two major cratons in Northeast Asia.

The steps used in this theoretical example are as follows.

1. A regional geologic base map is constructed. In figure 1*A*, which shows a map view of an orogenic belt (consisting of two cratons and several intervening terranes), are two major cratons (A, B), several fault-bounded terranes (1, 2, 3, 4) between the two cratons, two accretionary assemblages (a,b), and three postaccretionary overlap assemblages (c,d,e).
2. A group of mineral-deposit models appropriate for the geology are identified and defined, and a mineral deposit database is prepared. In this theoretical example, the major applicable mineral-deposit models are low-sulfide Au-Ag quartz vein (orogenic gold), ironstone, Au epithermal vein, porphyry Cu, bedded barite, and kuroko massive sulfide.
3. Metallogenic belts are delineated. For simplicity in this example each belt is assumed to contain only a single mineral deposit type, and two cratons (A, B) each contain distinctive, preaccretionary metallogenic belts including ironstone and bedded barite deposits that formed early in their geologic history. Island-arc terrane 4 contains a preaccretionary metallogenic belt of kuroko massive sulfide deposits that formed during marine arc volcanism. Between terranes 1 and 2 is a postaccretionary overlap assemblage of rocks which contain a group of Au-quartz vein deposits that formed during the accretion of terrane 1 to terrane 2. Between terranes 3 and 4 is accretionary assemblage *a* that consists of a collisional granitic pluton with a porphyry Cu belt that formed during accretion of terrane 3 against terrane 4. Overlying all of the terranes and both cratons is postaccretionary overlap assemblage *e* that contains a metallogenic belt with Au-Ag epithermal vein deposits.
4. The genesis of bedrock geologic units, structures, and contained metallogenic belts and mineral deposits is interpreted using modern tectonic concepts, for example: kuroko massive sulfide deposits forming in an island-arc terrane environment; porphyry Cu and low-sulfide

Au-quartz vein deposits forming in a collisional environment; and epithermal Au vein deposits forming in a continental-margin arc environment.

5. By carefully defining each metallogenic belt to be geologically favorable for a group of coeval and genetically-related mineral deposits, a predictive characteristic is identified within each metallogenic belt for possible undiscovered deposits.

Example of a Metallogenic-Tectonic Model

The six steps for performing a combined metallogenic and tectonic analysis are illustrated in figure 2.

The construction of a regional geologic base map and a metallogenic belt overlay is illustrated in figures 2*A* and 2*B*. For the delineation of metallogenic belts, the following main principles are used (Nokleberg and others, 2005; Rodionov and others, 2004): (1) *Mineral deposit association.* Each metallogenic belt includes a single mineral deposit type or a group of spatially and genetically-related mineral deposits types. (2) *Tectonic event for formation of mineral deposits.* Each metallogenic belt includes a group of coeval and genetically related mineral deposits that formed as the result of a specific tectonic event (for example, subduction-related igneous arc, collision, accretion, rifting, and so on). (3) *Favorable geological, geochemical, and geophysical environment.* Each metallogenic belt contains host rocks, structures, geochemical anomalies or signatures, and(or) geophysical anomalies or signatures that are favorable for the occurrence of a particular suite of mineral deposit types. (4) *Geological or tectonic boundaries.* Each metallogenic belt typically is bounded by contacts with favorable stratigraphic or magmatic units, or by major faults (sutures) along which substantial translations have commonly occurred.

The components of a mineral deposit database and assignment of mineral-deposit models are listed in figure 2*C*.

The synthesis of a metallogenic-tectonic model, as listed in figure 2*D*, consists of seven steps: (1) tectonic environments for the cratons, cratonal margins, orogenic collages of terranes, overlap assemblages, and contained metallogenic belts are assigned from regional compilation and synthesis of stratigraphic, structural, metamorphic, isotopic, paleomagnetic, faunal, and provenance data (for example, Nokleberg and others, 2000; Scotese and others, 2001); (2) correlations are made among terranes, fragments of overlap assemblages, and

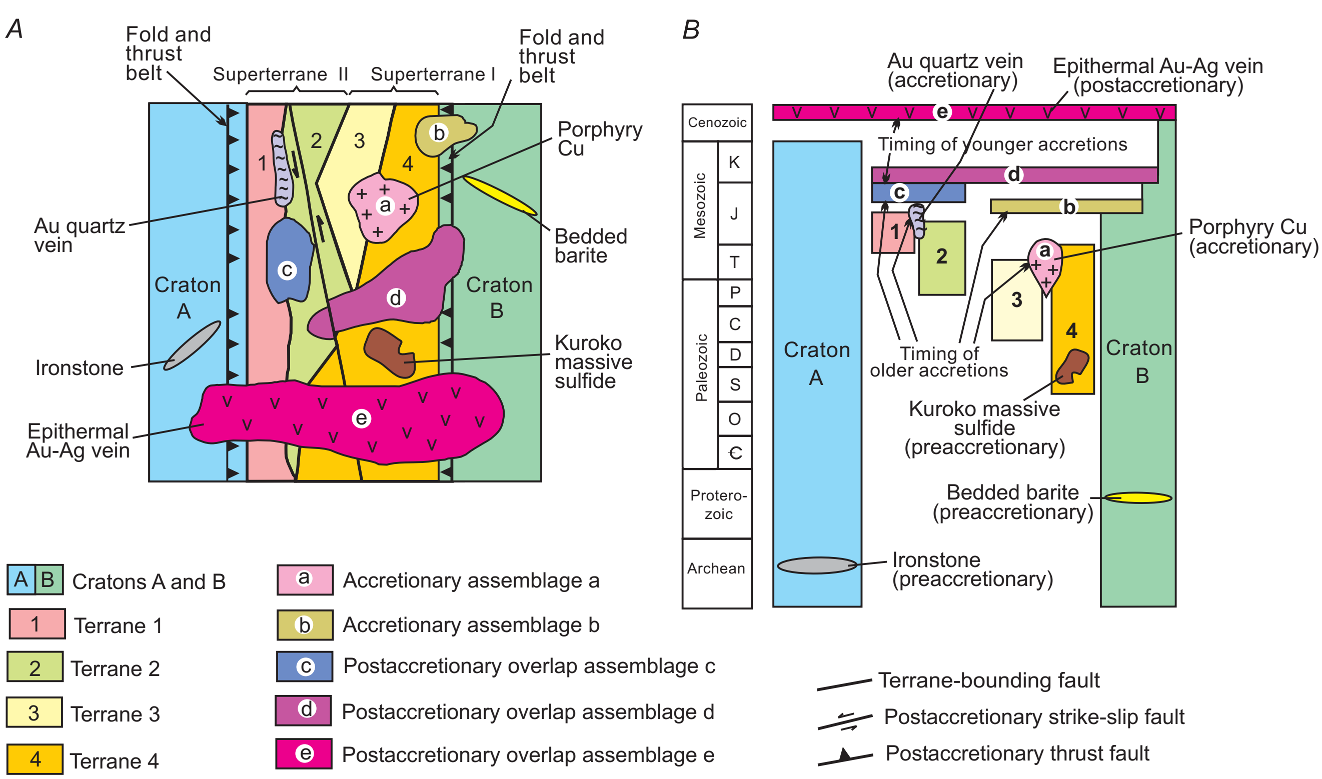

Figure 1. Schematic diagram illustrating methodology of combined regional and metallogenic and tectonic analysis of cratons, terranes, accretionary assemblages, post-accretopmaru overlap assemblages, and contained metallogenic belts. *A*. Map view of orogenic belt. *B*. Stratigraphic columns for orogenic belt. Adapted from Parfenov and others (1998)

fragments of contained metallogenic belts; (3) tectonic linkages are established between related terranes, such as an igneous-arc terrane and an associated subduction-zone terrane, for example, these linked terranes and their contained metallogenic belts, can be grouped into coeval, curvilinear arc-subduction-zone complexes that make up a tectonic collage; (4) from geologic, faunal, and paleomagnetic data, the original positions (loci) of terranes and their metallogenic belts are interpreted; (5) paths of tectonic migration of terranes and contained metallogenic belts are constructed; (6) the timings and nature of accretions of the terranes and contained collision-related metallogenic belts are determined from geologic, age, and structural data; (7) additional data for constructing the model are obtained from the geologic characteristics of postaccretionary overlap assemblages and contained metallogenic belts that overlie and stitch together the underlying and accreted or amalgamated terranes.

A simplified tectonic model that was synthesized using these data and the interpretations in parts 1-4 is illustrated in figure 2*E*.

The applications resulting from a combined metallogenic and tectonic analysis, as listed in figure 2*F*, include: (1) refining mineral-deposit models and deposit genesis; (2) improvement of assessments of undiscovered mineral resources as a part of quantitative mineral-resource assessment studies; (3) improvement of land-use and mineral exploration planning; (4) improvement of interpretations of the origins of host rocks, mineral deposits, and metallogenic belts; and (5) providing guidelines for new research.

Construction of a Regional Geologic Base Map

To compile a metallogenic-belt map for a metallogenic and tectonic analysis, a regional geologic base map must first be constructed that permits the display of metallogenic belts and their relations to host rock geology or host-rock structures (Nokleberg and others, 1997b,c; Parfenov and others, 2003, 2004a,b). To facilitate the analysis of the crustal origin and evolution of mineralizing systems, the geologic base map must be constructed at a scale that shows the major geologic data required for a synthesis that should reveal the tectonic origin of the host-rock geologic units and structures that controlled the formation of groups of mineral deposits in the metallogenic belts.

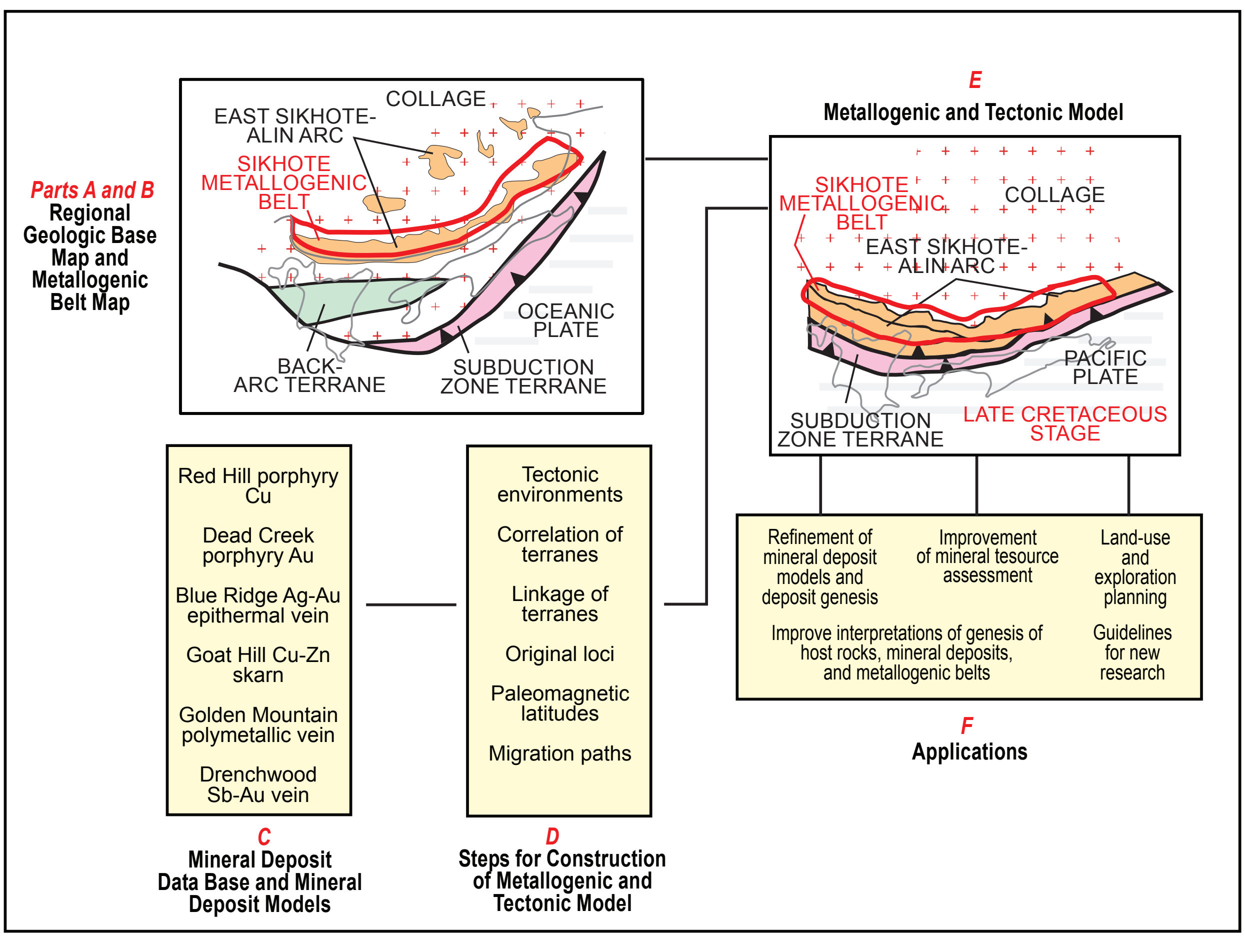

Figure 2. Major components of a metallogenic and tectonic analysis and synthesis of a metallogenic-tectonic model. *A, B,* Regional geologic base map and metallogenic belt map. *C,* Mineral deposit database and mineral-deposit models. *D,* Steps for synthesis of a metallogenic-tectonic model. *E,* Metallogenic-tectonic model. *F,* Applications.

For example. a summary geodynamics map of Northeast Asia (fig. 3; from Parfenov and others, 2003, 2004a,b) shows the host rock geology and structures that are related to the origin of metallogenic belts, including: (1) the regional surface extent of major geologic units (cratons, cratonal margins, tectonic collages of island-arc terrane, continental-margin arc, accretionary wedge, and passive continental margin terranes, volcanic and plutonic igneous arcs); (2) major fault and rift systems; and (3) active subduction zones. The regional-geologic base map should also provide descriptive data on the tectonic origins of major host-rock geologic units (for example, explanation, fig. 3) that are needed to establish geologic controls on the metallogenic belts. Figure 3 utilizes the concept of tectonic collage (see definition above) which enables: (1) depiction at small (regional) scales of the major geologic units and structures that formed in a single tectonic event; and (2) depiction of the major metallogenic belts related to the tectonic collages.

Interpretation of Tectonic Environments

For a modern metallogenic and tectonic analysis, interpretation of tectonic environments is essential for determining the origins of major geologic units and their contained mineral deposits and metallogenic belts. The interpretation of tectonic environment permits the linking of geologic origins for these sometimes disparate datasets. For the metallogenic and tectonic analyses of Northeast Asia and the Circum-North Pacific (table 1; Nokleberg and others, 1997b,c, 2000, 2005; Scotese and others, 2001; Obolenskiy and others, 2003 and this volume; Parfenov and others, 2003, 2004a,b), the major geologic units (terranes, overlap assemblages, plates), mineral deposits, mineral deposit types, and metallogenic belts, are interpreted according to the following tectonic environments: (1) craton and cratonal margin; (2) passive continental margin; (3) metamorphosed continental margin; (4) continental-margin arc and backarc; (5) island-arc terrane and backarc; (6) oceanic crust, seamount, or ophiolite related to rifting and sea-floor spreading; (7) accretionary wedge and subduction zone; (8) turbidite basin; (9) collisional; (10) transform continental-margin faulting and associated bimodal volcanic-plutonic belt; (11) plume; and (12) metamorphic. (See definitions above.) For terranes with complex geologic histories, the chosen tectonic environment is the one most prevalent during the history of the terrane. This assignment of tectonic environments should result in a higher quality interpretation for the origin of mineral deposits and metallogenic belts and for the origin of the geologic units and structures in which the deposits and belts formed.

Description of Significant Mineral Deposits and Synthesis of Mineral-Deposit models

Part of the core dataset for a combined metallogenic and tectonic analysis is a high-quality description of significant known mineral deposits (see above definition) in the region. For example, descriptions of selected major Middle Jurassic through Early Cretaceous lode deposits for Northeast Asia, adapted from Ariunbileg and others (2003), are listed in table 2 along with descriptive data that enable the determination of mineral-deposit models, age and relation of deposits and their relations to host rocks, and tectonic origins.

A modern regional metallogenic and tectonic analysis requires the construction of mineral-deposit models appropriate for the region. The models can subsequently be used to classify mines, mineral deposits, and prospects that can be interpreted as forming during various regional tectonic processes. The beginning of this type of correlation between models and tectonic processes is evident in many of classic compilations of mineral deposits models (Eckstrand, 1984; Cox and Singer, 1986; Singer, 1993). For example, mineral-deposit models employed for a large region and lists the mineral-deposit models that were defined and described for a metallogenic and tectonic analysis of Northeast Asia are listed in table 3. For this large and complex region, 122 mineral-deposit models were required to describe the characteristic features of the 1,674 lode deposits and 75 placer districts. The models include previous descriptions by Eckstrand (1984), Cox and Singer (1986), and Nokleberg and others (1997a), with modifications by Obolenskiy and others (2003, this volume).

The mineral-deposit models listed in table 3 consist both of descriptive and genetic information that is systematically arranged in order to define the essential properties of a class or type of mineral deposit. Some models, however, are based mainly on descriptive (empirical) information, whereby the various attributes are recognized as essential even though the nature of their relationships is unknown. For example, in the basaltic Cu mineral-deposit type, the empirical datum of a geologic association of Cu sulfides with relatively Cu-rich metabasalt or greenstone is the essential attribute. Some other mineral-deposit models are defined by genetic (theoretical) considerations in which case the attributes are related through some fundamental geologic process. For example, the W skarn mineral-deposit model type, the genetic process of contact metasomatism is the essential attribute. For additional information on the methodology for defining mineral-deposit models, see the discussions by Eckstrand (1984), Kirkham (1993), and Cox and Singer (1986).

Compilation of a Metallogenic-Belt Map

Many metallogenic maps that display major mineral deposits and (or) districts on a regional geologic base map are typically complex because of a high density of deposits. To simplify the data and increase understanding of regional patterns, the concept of a metallogenic belt map was developed for Northeast Asia and the Circum-North Pacific (Nokleberg and others, 1998; Obolenskiy and others, 2003, 2004). The display of metallogenic belts, as defined above, enables the depiction of major groups of coeval and genetically related, significant lode and placer deposits that can be interpreted as having formed in a single major geologic or tectonic event. A requirement of a metallogenic belt map is that the various belts can be related to major host-rock geologic units or structures as portrayed on the map and accompanying explanation. Examples of summary metallogenic belt maps for Northeast Asia are shown in the various time-stage chapters on regional metallogenic and tectonic analysis in this volume. More detailed metallogenic belt maps and companion descriptions are published by Obolenskiy and others (2003) and Rodionov and others (2004).

Benefits of Performing a Combined Regional Metallogenic and Tectonic Analysis

As described above, a high-quality, combined metallogenic and tectonic analysis can benefit other mineral resource studies, including: (1) refinement of mineral-deposit models and deposit genesis (Eckstrand, 1984; Cox and Singer, 1986; Singer and Cox, 1988; Kirkham, 1993); (2) improvement of estimates of undiscovered mineral resources as a part of quantitative mineral resource assessments (Cox, 1993; Singer, 1993, 1994); (3) improvement of land-use planning and mineral exploration; (4) improvement of interpretation of the origins of host rocks, mineral deposits, and metallogenic belts; and (5) suggestion of guidelines for future research.

Three examples of these benefits are as follows. (1) Indepth understanding of the tectonic and metallogenic origins of potential host rocks for mineral deposits enables the prediction of undiscovered mineral deposits according to favorable host rock geology. This capability is crucial because for a proper mineral resource assessment, the outlines of permissive tracts (that is, areas with a potential for undiscovered mineral deposit types) must be drawn for each mineral deposit type on the basis of knowledge of favorable geologic environments. (2) Regional metallogenic-tectonic analyses, such as those performed for Northeast Asia and the Circum-North Pacific, enable the identification and location of continuations of ore-hosting terranes and permissive tracts worldwide that have been separated by tectonic processes. For example, suppose that a suite of metallogenic belts containing porphyry Cu deposits are hosted in fragments of island-arc terranes which are now dispersed in a collage of terranes in the center of a continent. Tectonic analysis of the origin of the island-arc terranes and correlations with each other can produce a grouping of these terranes and their contained metallogenic belts into an originally continuous island arc and a single, large metallogenic belt. This enlargement of the host-rock area and its contained metallogenic belts will establish a larger dataset that can greatly improve the quality of metallogenic and tectonic analysis and mineral-resource assessment. (3) Understanding the metallogenic setting and history of host rocks and ore-forming processes often is important for estimating the number of undiscovered mineral deposits in a permissive tract. For example, the number of volcanogenic massive sulfide deposits estimated in a permissive tract containing poorly exposed and poorly described mafic to felsic volcanic rocks may vary depending on whether the tract is located in a volcanic forearc, axial-arc, or backarc tectonic setting. Conversely, no deposits of this type would be estimated for a tract of similar rocks in an extensional cratonic setting.

Summary

This chapter presents an overview of the methodology of combined regional metallogenic and tectonic analysis, including definitions, theoretical examples, and known examples for the Middle Jurassic through Early Cretaceous of Northeast Asia. It also describes how a high-quality metallogenic and tectonic analysis, and synthesis of an associated metallogenic-tectonic model, can benefit: (1) refinement of mineral-deposit models and deposit genesis; (2) improvement of estimates of undiscovered mineral resources as a part of quantitative mineral resource assessments; (3) improvement of land-use planning and mineral exploration; (4) improvement of interpretations of the origins of host rocks, mineral deposits, and metallogenic belts; and (5) suggestion of guidelines for future research. A major goal of this chapter is to demonstrate that the methodology of regional metallogenic and tectonic analysis, as summarized herein, is a powerful theoretical tool for defining, analyzing, and interpreting the crustal origin and evolution of mineralizing systems throughout geologic space and time.

Acknowledgments

Since the late 1970's, many persons have assisted us in developing and employing the concepts of combined regional metallogenic and tectonic analysis and in developing methods for synthesizing a metallogenic-tectonic model, including D.P. Cox, D.L. Jones, E.M. MacKevett, Jr., Ian O. Norton, D.W. Scholl, C.R. Scotese, and D.A. Singer, and D.B. Stone. We also thank managers N.L. Dobretsov, L.C. Gundersen, P.P. Hearn, K. Johnson, R. Koski, L.P. Leahy, J. Medlin, M. Power, and J.N. Weaver for their encouragement and support of the project. We appreciate the constructive reviews of D.A. John and J.F. Slack.

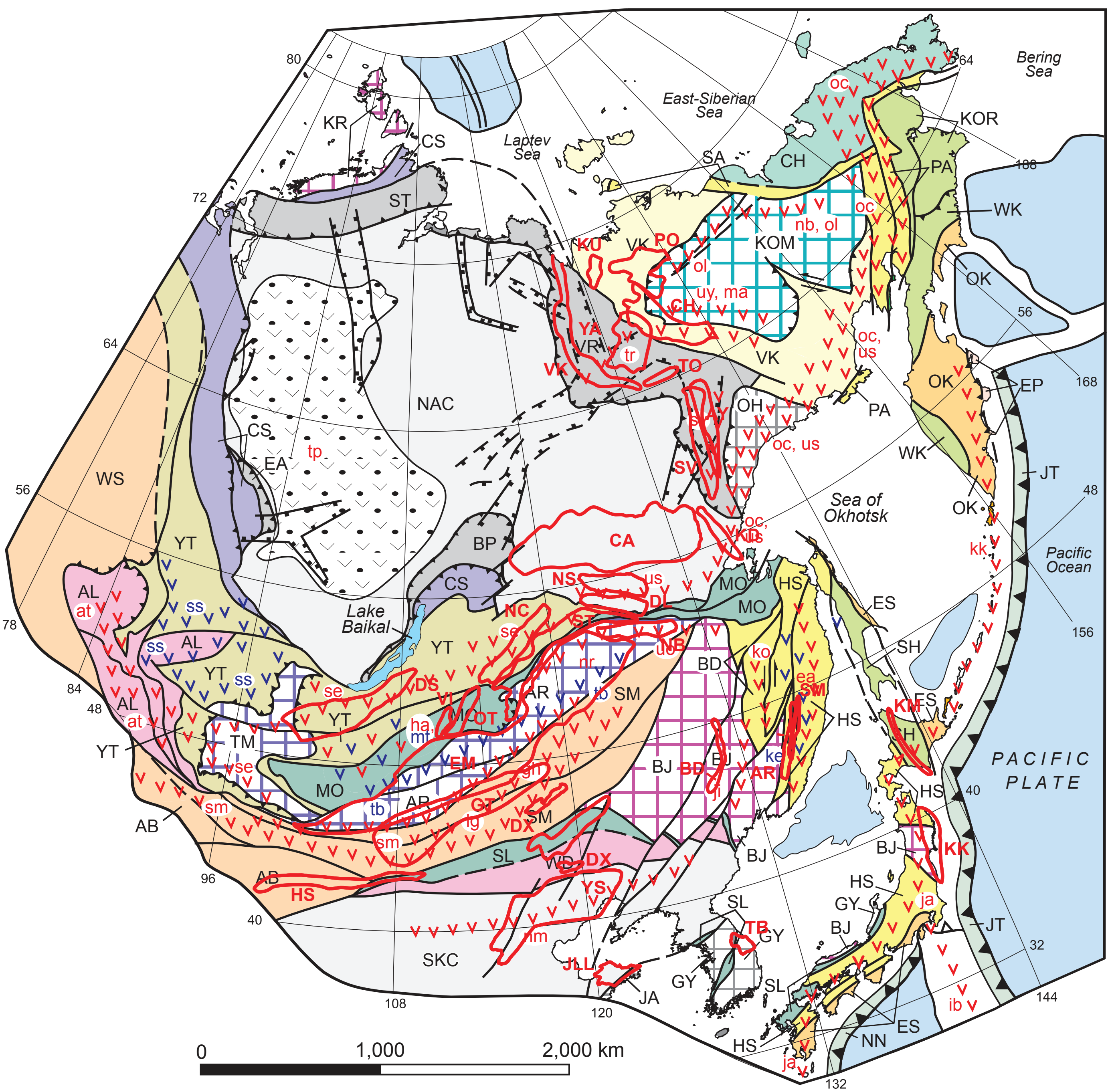

Figure 3. Summary geodynamic map of Northeast Asia showing outlines of major metallogenic belts for the Middle Jurassic through Early Cretaceous. Adapted from Obolenskiy and others (2003, 2004) and Parfenov and others (2003, 2004). Regional geology for area east of 144°E longitude (eastern boundary of Northeast Asia project area) as described and interpreted by Nokleberg and others (2000, 2005).

EXPLANATION

Cratons and Cratonal Margins

Cratons: NAC - North Asian (Archean and Proterozoic); SKC - Sino-Korean (Archean and Proterozoic)

Cratonal Margin: BP - Baikal-Patom (Riphean through Cambrian and older basement; EA - East Angara (Riphean and older basement; ST - South Taimyr (Ordovician through Jurassic); VR - Verkhoyansk (Devonian through Jurassic).

Tectonic Collages Between the North Asian and Sino-Korean Cratons

CS - Circum-Siberia (Proterozoic)

YT - Yenisey-Transbaikal (Vendian through Early Ordovician)

AL - Altay (Vendian to Ordovician)
WD - Wundurmiao (Riphean through Ordovician)

AB - Atasbogd (Ordovician through Permian); SM - South Mongolia-Khingan (Ordovician through Carboniferous); WS - West Siberian (Ordovician through Carboniferous)

MO - Mongol-Okhotsk (Devonian through Late Jurassic); SL - Solon (Carboniferous and Permian)

Tectonic Collages Along the Northern and Eastern Margins of North Asian and Sino-Korean Cratons

CH - Chukotka (Paleozoic and Triassic)

VK - Verkhoyansk-Kolyma Paleozoic through Early Jurassic)

BD - Badzhal (Triassic through Early Cretaceous); PA - Penzhina-Anadyr (Late Jurassic and Cretaceous); HS - Honshu-Sikhote-Alin (Jurassic and Early Cretaceous); SA - South Anyui (Permian through Jurassic);

KOR - Koryak (Late Jurassic through Paleocene; SH - Sakhalin-Hokkaido (Cretaceous); WK - West Kamchatka (Mid-Cretaceous through Early Tertiary)

ES - East Sakhalin (Late Cretaceous and Early Tertiary); OK - Olyutorka-Kamchatka (Late Cretaceous to Paleocene)

EP - East Kamchatka Peninsular (Mainly Paleocene)

Active Subduction Zones

JT- Japan Trench (including Kuril-Kamchatka trench) (Miocene through Holocene; NN - Nankai (Miocene through Holocene)

Cratonal Terranes and Superterranes

Cratonal terranes (Archean and Proterozoic): GY - Gyeonggi-Yeongnam; JA - Jiaonan; OH - Okhotsk

Late Proterozoic and Cambrian superterranes: AR - Argun-Idermeg; TM - Tuva-Mongolia

Archean through Permian superterranes: BJ - Bureya-Jiamusi; KR - Kara

Jurassic Superterrane: KOM - Kolyma-Omolon (Archean through Jurassic)

Pelagic and Oceanic Rocks

Surficial deposits

Oceanic crust

Overlap Continental-Margin Arcs and Igneous Belts

at - Altay arc (Devonian and early Carboniferous, 381 to 290 Ma)
ea - East Sikhote-Alin arc (Late Cretaceous through early Tertiary, 96-65 Ma)
gh - Gobi-Khankaisk-Daxing'anling arc (Permian, 295 to 250 Ma)
ha - Hangay arc (Late Carboniferous and Early Permian, 320 to 272 Ma)
ji - Jihei arc (Permian, 295 to 250 Ma)
ko - Khingan arc (Early and mid-Cretaceous)
lg - Lugyngol arc (Permian and Triassic, 295 to 250 Ma)
ma Main granite belt (Late Jurassic, 144 to 134 Ma)
nb - Northern granite belt (Early Cretaceous, 138 to 120 Ma)
nm - North Margin (Late Carboniferous and Permian, 320 to 272 Ma)
nr - Norovlin arc (Devonian and Early Carboniferous, 410 to 255 Ma)
oc - Okhotsk-Chukotka arc (Late Cretaceous and early Tertiary, 96 to 53 Ma)
ol - Oloy arc (Late Jurassic, 154 to135 Ma)
se - Selenga arc (Permian through Jurassic, 295 to135 Ma)
sm - South Mongolian arc (Carboniferous through Triassic, 320 to 203 Ma)
ss - South Siberian arc (Devonian)
sv - South Verkhoyansk granite belt (Late Jurassic through mid-Cretaceous, 157 to 93 Ma)
tr - Transverse granite belt (Early Cretaceous, 134 to 124 Ma)
uo - Umlekan-Ogodzhin arc (Cretaceous, 135 to 65 Ma)
us - Uda-Murgal and Stanovoy arc (Jurassic and Early Cretaceous, 203 to 96 Ma)
uy - Uyandina-Yasachnaya arc (Late Jurassic and Early Cretaceous, 154 to 120 Ma)

Plume-Related Igneous Province

tp - Tungus Plateau igneous province - (Late Permian and Early Triassic, 245 Ma)

Active Arcs

ib - Izu-Bonin (late Cenozoic, 20 to 0 Ma)
ja - Japan (late Cenozoic, 23 to 0 Ma)
kk - Kuril-Kamchatka (late Cenozoic, 11 to 0 Ma)

Transpressional Arcs

ke - Kema (Mid-Cretaceous)
mt - Mongol-Transbaikal (Late Triassic through Early Cretaceous, 230 to 96 Ma)
ss - South Siberian (Early Devonian, 415 to 400 Ma)
tb - Transbaikalian-Daxinganling (Middle Jurassic through Early Cretaceous,175 to 96 Ma)

Symbols, Faults, and Contacts

Overlap-continental-margin arc
Transform-continental-margin arc
Active subduction zone
Thrust
Strike-slip fault
Fault
Contact
Riphean aulacogen
Devonian aulacogen
Modern rift system (Gakkel Ridge)
os Metallogenic belt

Figure 3.—Continued.

References Cited

Ariunbileg, S., Biryul'kin, G.V., Byamba, J., Davydov, Y.V., Dejidmaa, G., Distanov, Dorjgotov, G., G.N., Gerel, O., Fridovskiy, V.Yu., Gotovsuren, A., Hwang, D., Kochnev, A.P., Kostin, A.V., Kuzmin, M.I., Letunov, S.A., Li, J., Li, X., Malceva, G.D., Melnikov, V.D., Nikitin, V.M., Obolenskiy, A.A., Ogasawara, M., Orolmaa, D., Parfenov, L.M.,. Popov, N.V., Prokopiev, A.V., Ratkin, V.V., Rodionov, S.M., Seminskiy, Z.V., Shpikerman, V.I., Smelov, A.P., Sotnikov, V.I., Spiridonov, A.V., Stogniy, V.V., Sudo, S., Sun, F., Sun, J., Sun, W.,. Supletsov, V.M., Timofeev, V.F., Tyan, O.A., Vetluzhskikh, V.G., Xi, A., Yakovlev, Y.V., Yan, H., Zhizhin, V.I., Zinchuk, N.N., and Zorina, L.M., 2003, Significant metalliferous and selected non-metalliferous lode deposits, and selected placer districts of Northeast Asia: U.S. Geological Survey Open-File Report 03-220, 422 p. [CD-ROM]

Ariunbileg, Sodov, Biryul'kin, G.V., Byamba, Jamba, Davydov, Y.V., Dejidmaa, Gunchin, Distanov, FOR EXAMPLE, Dorjgotov, Gamyanin, G.N., Gerel, Ochir, Fridovskiy, V.Yu., Gotovsuren, Ayurzana, Hwang, Duk Hwan, Kochnev, A.P., Kostin, A.V., Kuzmin, M.I., Letunov, S.A., Li, Jiliang, Li, Xujun, Malceva, G.D., Melnikov, V.D., Nikitin, V.M., Obolenskiy, A.A., Ogasawara, Masatsugu, Orolmaa, Demberel, Parfenov, L.M.,. Popov, N.V., Prokopiev, A.V., Ratkin, V.V., Rodionov, S.M., Seminskiy, Z.V., Shpikerman, V.I., Smelov, A.P., Sotnikov, V.I., Spiridonov, A.V., Stogniy, V.V., Sudo, Sadahisa, Sun, Fengyue, Sun, Jiapeng, Sun, Weizhi,. Supletsov, V.M., Timofeev, V.F., Tyan, O.A., Vetluzhskikh, V.G., Xi, Aihua, Yakovlev, Y.V., Yan, Hongquan, Zhizhin, V.I., Zinchuk, N.N., and Zorina, L.M., 2003, Significant metalliferous and selected non-metalliferous lode deposits, and selected placer districts of Northeast Asia: U.S. Geological Survey Open-File Report 03-220, 422 p. [CD-ROM].

Cox, D.P., 1993, Estimation of undiscovered deposits in quantitative mineral resource assessments—Examples from Venezuela and Puerto Rico: Nonrenewable Resources, v. 2, p. 82–91.

Cox, D.P., and Singer, D.A., eds., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Eckstrand, O.R., 1984, Canadian mineral deposit types—A geological synopsis: Geological Survey of Canada Economic Geology Report 36, 86 p.

Gauthier, M., and Brown, A.C., 1986, Zinc and iron metallogeny in the Maniwaki-Gracefield District, southwestern Quebe: *Economic Geology,* v. 81; p. 89-112.

Howell, D.G., Jones, D.L., and Schermer, E.R., 1985, Tectonostratigraphic terranes of the Circum-Pacific region: Principles of terrane analysis, *in* Howell, D.G., ed., Tectonostratigraphic terranes of the Circum-Pacific region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, p. 3-31.

Jones, D.L., Howell, D.G., Coney, P.J., and Monger, J.W.H., 1983, Recognition, character, and analysis of tectonostratigraphic terranes in western North America, in Hashimoto, M., and Uyeda, S., eds., Accretion tectonics in the circum-Pacific regions; Proceedings of the Oji International Seminar on Accretion Tectonics, Japan, 1981; Advances in Earth and Planetary Sciences: Tokyo, Terra Scientific, p. 21-35.

Kirkham, R.V., ed., 1993, Mineral deposit modeling: Geological Association of Canada Special Paper 40, 770 p.

Naumova, V.V., Miller, R.M., Mikhail I. Patuk, M.I., Kapitanchuk, M.U., Nokleberg, W.J., Khanchuk, A.I., Parfenov, L.M., and Rodionov, S.M., 2006, Geographic information systems (GIS) spatial data compilation of geodynamic, tectonic, metallogenic, mineral deposit, and geophysical maps and associated descriptive data for Northeast Asia, U.S. Geological Survey Open-File Report 2006-1150 [CD-ROM].

Nokleberg, W.J., Badarch, Gombosuren, Berzin, N.A., Diggles, M.F., Hwang, D., Khanchuk, A.I., Miller, R.J. Naumova, V.V., Obolenskiy, A.A., Ogasawara, M., Parfenov, L.M., Prokopiev. A.V., Rodionov, S.M., and Hongquan, Yan, eds., 2004, Digital files for Northeast Asia geodynamics, mineral deposit location, and metallogenic belt maps, stratigraphic columns, descriptions of map units, and descriptions of metallogenic belts: U.S. Geological Survey Open-File Report 2004-1252 [CD-ROM].

Nokleberg, W.J., Bundtzen, T.K., Dawson, K.M., Eremin, R.A., Goryachev, N.A., Koch, R.D. Ratkin, V.V., Rozenblum, I.S., Shpikerman, V.I., Frolov, Y.F., Gorodinsky, M.E., Melnikov, V.D., Diggles, M.F., Ognyanov, N.V., Petrachenko, E.D., Petrachenko, R.I., Pozdeev, A.I., Ross, K.V., Wood, D.H., Grybeck, Donald, Khanchuk, A.I., Kovbas, L.I., Nekrasov, I.Ya., and Sidorov, A.A., 1997a, Significant metalliferous lode deposits and placer districts for the Russian Far East, Alaska, and the Canadian Cordillera: U.S. Geological Survey Open-File Report 96-513-B [CD-ROM].

Nokleberg, W.J., Bundtzen, T.K., Dawson, K.M., Eremin, R.A., Ratkin, V.V., Shpikerman, V.I., Goryachev, N.A., Khanchuk, A.I., Koch, R.D., Rozenblum, I.S., Gorodinsky, M.E., Frolov, Y.F., Pozdeev, A.I., Parfenov, L.M., and Sidorov, A.A., 1997b, Mineral deposit and metallogenic belt maps of the Russian Far East, Alaska, and the Canadian Cordillera: Geological Survey of Canada Open File 3446, 7 sheets, scales 1:5,000,000,1:10,000,000.

Nokleberg, W.J., Bundtzen, T.K., Eremin, R.A., Ratkin, V.V., Dawson, KM., Shpikerman, V.I., Goryachev, N.A., Byalobzhesky, S.G., Frolov, Y.F., Khanchuk, A.I., Koch, R.D., Monger, J.W.H., Pozdeev, A.I., Rozenblum, I.S., Rodionov, S.M., Parfenov, L.M., Scotese, C.R., and Sidorov, A.A., 2005, Metallogenesis and tectonics of the Russian Far East, Alaska, and the Canadian Cordillera: U.S. Geological Survey Professional Paper 1697, 397 p.

Nokleberg, W.J., Parfenov, L.M., Monger, J.W.H., Baranov, B.V., Byalobzhesky, S.G., Bundtzen, T.K., Feeney, T.D., Fujita, Kazuya, Gordey, S.P., Grantz, A., Khanchuk, A.I., Natal'in, B.A., Natapov, L.M., Norton, I.O., Patton, W.W., Jr., Plafker, G., Scholl, D.W., Sokolov, S.D., Sosunov, G.M., Stone, D.B., Tabor, R.W., Tsukanov, N.V., and Vallier, T.L., 1997c, Summary Circum-North Pacific tectono-stratigraphic terrane map: U.S. Geological Survey, Open File Report 96-727, scale 1:10,000,000.

Nokleberg, W.J., Parfenov, L.M., Monger, J.W.H., Norton, I.O., Khanchuk, A.I., Stone, D.B., Scholl, D.W., and Fujita, K., 2000, Phanerozoic tectonic evolution of the Circum-North Pacific: U.S. Geological Survey Professional Paper 1626, 122 p.

Nokleberg, W.J., West, T.D., Dawson, K.M., Shpikerman, V.I., Bundtzen, T.K., Parfenov, L.M., Monger, J.W.H., Ratkin, V.V., Baranov, B.V., Byalobzhesky, S.G., Diggles, M.F., Eremin, R.A., Fujita, Kazuya, Gordey, S.P., Gorodinskiy, M.E., Goryachev, N.A., Feeney, T.D., Frolov, Y.F., Grantz, A., Khanchuk, A.I., Koch, R.D., Natalin, B.A., Natapov, L.M., Norton, I.O., Patton, W.W.. Jr., Plafker, G., Pozdeev, A.I., Rozenblum, I.S., Scholl, D.W., Sokolov, S.D., Sosunov, G.M., Stone, D.V., Tabor, R.W., Tsukanov, N.V., and Vallier, T.L., 1998, Summary terrane, mineral deposit, and metallogenic belt maps of the Russian Far East, Alaska, and the Canadian Cordillera: U.S. Geological Survey Open-File Report 98-136 [CD-ROM].

Obolenskiy, A.A., Rodionov, S.M., Ariunbileg, S., Dejidmaa, G., Distanov, Dorjgotov, D., Gerel, O., Hwang, D., Sun, F., Gotovsuren, A., Letunov, S.N., Li, X., Nokleberg, W.J., Ogasawara, M., Seminsky, Z.V., Smelov, A.P., Sotnikov, V.I., Spiridonov, A.A., Zorina, L.V., and Yan, H., 2003, Mineral deposit models for Northeast Asia, *in* Nokleberg, W.J., Miller, R.J., Naumova, V.V., Khanchuk, A.I., Parfenov, L.M., Kuzmin, M.I., Bounaeva, T.M., Obolenskiy, A.A., Rodionov, S.M., Xeminskiy, Z.V., and Diggles, M.F., eds.: Preliminary Publications Book 2 from Project on Mineral Resources, Metallogenesis, and Tectonics of Northeast Asia: U.S. Geological Survey Open-File Report 03-203, 44 p. [CD-ROM].

Obolenskiy, A.A. Rodionov, S.M. Dejidmaa, G., Gerel, O., Hwang, D.H., Miller, R.J., Nokleberg, W.J., Ogasawara, M., Smelov, A. P., Yan, H., and Seminskiy, Z.V., 2004, Metallogenic belt and mineral deposit maps for Northeast Asia: U.S. Geological Survey Open-File Report 2004-1252, 4 sheets, scales 1:7,500,000, 1:15,000,000; 442 p. [CD-ROM].

Obolenskiy, A.A., Rodionov, S.M., Dejidmaa, G., Gerel, O., Hwang, D., Miller, R.J., Nokleberg, W.J., Ogasawara, M., Smelov, A.P., Yan, H., and Seminskiy, Z.V., with compilations on specific regions by Ariunbileg, S., Biryul'kin, G.B., Byamba, J., Davydov. Y.V., Distanov, Dorjgotov, D., Gamyanin, G.N., Fridovskiy, V.Yu., Goryachev, N.A., Gotovsuren, A., Khanchuk, A.I., Kochnev, A.P., Kostin, A.V., Kuzmin, M.I.,. Letunov, S.A., Li, J., Li, Xujun, Malceva, G.D., Melnikov, V.D., Nikitin, V.M., Parfenov, L.M., Popov, N.V., Prokopiev, A.V., Ratkin, V.V., Shpikerman, V.I., Sotnikov, V.I., Spiridonov, A.V., Stogniy, V.V., Sudo, S., Sun, F., Sun, J., Sun, W., Supletsov, V.M., Timofeev, V.F., Tyan, O.A., Vetluzhskikh, V.G., Wakta, K., Xi, A., Yakovlev, Y.V., Zhizhin, V.I., Zinchuk, N.N., and Zorina, L.M., 2003, Preliminary metallogenic belt and mineral deposit location maps for Northeast Asia: U.S. Geological Survey Open-File Report 03-203, 143 p., 4 sheets, scales1:7,500,000; 1:15,000,000.

Parfenov, L.M., Khanchuk, A.I., Badarch, G., Berzin, N.A., Hwang, D.H., Miller, R.J., Naumova, V.V., Nokleberg, W.J., Ogasawara, M., Prokopiev, A.V., and Yan, H., 2004a, Generalized Northeast Asia geodynamics map: U.S. Geological Survey Open-File Report 2004-1252, scale 1:15,000,000 [CD-ROM].

Parfenov, L.M., Khanchuk, A.I., Badarch, G., Berzin, N.A., Miller, R.J., Naumova, V.V., Nokleberg, W.J., Ogasawara, M., Prokopiev, A.V., and Yan, H., 2004b, Descriptions of overlap assemblages and tectono-stratigraphic terranes, definitions, and methods for compilation for Northeast Asia geodynamics map: U.S. Geological Survey Open-File Report 2004-1252, 167 p. [CD-ROM].

Parfenov, L.M., Khanchuk, A.I., Badarch, G., Miller, R.J., Naumova, V.V., Nokleberg, W.J., Ogasawara, M., Prokopiev, A.V., and Yan, H., with contributions on specific regions by Belichenko, V., Berzin, N.A., Bulgatov, A.N., Byamba, J., Deikunenko, A.V., Dong, Y., Dril, S.I., Gordienko, I.V., HwangD., Kim, B.I., Korago, E.A., Kos'ko, M.K., Kuzmin, M.I., Orolmaa, D., Oxman, V.S., Popeko, L.I., Rudnev, S.N., Sklyarov, E.V., Smelov, A.P., Sudo, S., Suprunenko, O.I., Sun, F., Sun, J., Sun, W., Timofeev, V.F., Tret'yakov, F.F., Tomurtogoo, O., Vernikovsky, V.A.,. Vladimiro, A.G., Wakita, K., Ye, M., and Zedgenizov, A.N., 2003, Preliminary Northeast Asia geodynamics map: U.S. Geological Survey Open-File Report 03-205, 2 sheets, scale 1:5,000,000.

Parfenov, L.M., Nokleberg, W.J., and Khanchuk, A.I. 1998, Principles of compilation and the main subdivisions of the legend of the geodynamic map of North and Central Asia, Russian Far East South, Korea and Japan: Geology of the Pacific Ocean, v. 17, p. 3-13 (in Russian).

Remane, J., 1998, Explanatory note to global stratigraphic chart, app. B. of Circular of International Subcommission on Stratigraphic Classification (ISSC) of IUGS Commission on Stratigraphy: International Union of Geological Sciences (IUGS) Commission on Stratigraphy, v. 93, 11 p.

Rodionov, S.M., Obolenskiy, A.A., Dejidmaa, G., Gerel, O., Hwang, D., Miller, R.J., Nokleberg, W.J., Ogasawara, M., Smelov, A.P., Yan, H., and Seminskiy, Z.V., 2004, Descriptions of metallogenic belts, methodology, and definitions for Northeast Asia mineral deposit location and metallogenic belt maps: U.S. Geological Survey Open-File Report 2004-1252, 442 p. [CD-ROM].

Scotese, C.R., Nokleberg, W.J., Monger, J.W.H., Norton, I.O., Parfenov, L.M., Bundtzen, T.K., Dawson, K.M., Eremin, R.A., Frolov, Y.F., Fujita, Kazuya, Goryachev, N.A., Khanchuk, A.I., Pozdeev, A.I., Ratkin, V.V., Rodinov, S.M., Rozenblum, I.S., Shpikerman, V.I., Sidorov, A.A., and Stone, D.B., 2001, *in* Nokleberg, W.J., and Diggles, M.F., eds., Dynamic computer model for the metallogenesis and tectonics of the Circum-North Pacific: U.S. Geological Survey Open-File Report 01-161 [CD-ROM].

Singer, D.A., 1993, Basic concepts in three-part quantitative assessments of undiscovered mineral resources: Nonrenewable Resources, v. 2, p. 69-81.

Singer, D.A., 1994, The relationship of estimated number of undiscovered deposits to grade and tonnage models in three–part mineral resource assessments—1994 [abs.]: International Association of Mathematical Geology, Geology Annual Conference, Mount Tremblant, Quebec, Canada, Papers and Extended Abstracts, p. 325–326.

Singer, D.A., and Cox, D.P., 1988, Applications of mineral deposit models to resource assessments. U.S. Geological Survey Yearbook, Fiscal Year 1987, p. 55-57.

Tables 1–3

Table 1. Summary of major areas, major tectonic environments (events), and associated major lode mineral-deposit models derived from metallogenic analyses of Northeast Asia, the Russian Far East, Alaska, and the Canadian Cordillera.

[Adapted from Nokleberg and others (2003), Scotese and others (2001), and Rodionov and others (2004)]

Area	Tectonic environment(s) or event(s)	Major mineral-deposit types
Northeast Asia and North American cratons and cratonal margins	Rifting	Sedimentary-exhalative Zn-Pb, polygenic REE, Cyprus massive sulfide, carbonate-hosted sulfide, various volcanogenic massive sulfide deposit types.
Ocean	Sea-floor spreading (oceanic crust, seamount, or ophiolite related to rifting)	Cyprus massive sulfide, various volcanogenic massive sulfide deposit types, podiform chromite.
North Asian and North American continental margins	Continental-margin arc intruding passive continental margin, turbidite basin, or metamorphosed continental margin. Back-arc. Structurally underlain by subduction zone.	Various porphyry, epithermal vein, polymetallic vein, skarn, greisen, pegmatite, volcanogenic massive sulfide deposit types, Besshi massive sulfide.
Ocean	Island-arc terrane and backarc	Various porphyry, epithermal vein, polymetallic vein, and skarn deposit types, granitoid-related Au veinz, zoned mafic-ultramafic Cr-PGE, mafic-ultramafic related Cu-Ni-PGE.
North Asian and North American continental margins	Collision and metamorphic	Au in shear zone and quartz vein, granitoid-related Au, various porphyry and skarn types, Au in black shale.
North Asian and North American continental margins	Transform-continental-margin faulting and associated bimodal volcanic-plutonic belt	Zoned mafic-ultramafic-PGE, Cr, and Ti; W skarn, porphyry Cu-Mo, Au-Ag epithermal vein, Au in shear zone and quartz vein, basaltic native copper, Cu-Ag quartz vein.
North Asian and North American cratons	Plume intrusion into craton or cratonal margin	Mafic-ultramafic related Cu-Ni-PGE, Fe-Ti and REE carbonatite, various porphyry, pegmatite, and skarn deposit types, metamorphic graphite, diamond-bearing kimberlite.

Table 2. Examples of selected granitoid-related Au deposits for selected deposits in Northeast Asia.

[Adapted from Ariunbileg and others (2003)]

Latitude Longitude	Deposit name Country Metallogenic belt	Major metals Minor metals Deposit model	Grade and tonnage
51º 56’ N 138º 47’ E	Agnie-Afanas’evskoye Russia Pilda-Limuri	Au Granitoid-related Au vein	Average grade of about 25 g/t Au, maximum grade up to 1-2 kg/t Au. Mined from 1936 to 1962 with production of 12 tonnes Au.
Summary: Deposit occurs in a vein system that ranges up 0.5 km wide and up to 1.0 km long. System occurs in an anticline formed in Early Cretaceous sandstone and siltstone. Several diorite dikes occur along joints that cross host rock bedding. Veins range from 200 to 700 m long and 5 to 10 cm wide, strike northeast, and dip moderately. Veins contain mainly quartz, carbonate, feldspar, chlorite, and sericite with as much as 1% ore minerals. Ore minerals are pyrite, arsenopyrite, antimonite, chalcopyrite, sphalerite, chalcocite, and gold, and rare cassiterite, wolframite, scheelite, and molybdenite. Pyrite is dominant and forms disseminations and thin veinlets in quartz. Arsenopyrite content is less than pyrite and occurs in high-grade zones. Gold grains range from 1 to 6 mm, and occur in bunches, thin veinlets, and rare octahedron crystals in fractured quartz. Host rocks are altered near quartz veins and contain as much as 2 to 4 g/t Au. **Reference**: Moiseenko and Eyrish (1996).			
53º 27’ N 126º 27’ E	Pioneer Russia North Bureya	Au Granitoid-related Au vein	Average grade of 2.7 g/t Au, and 5.2 g/t Ag. Reserves of 17.1 tonnes Au, 20.1 tonnes Ag.
Summary: Deposit occurs near margin of an Early Cretaceous granodiorite intrusion in both the intrusion and in adjacent country rock that consists of contact-metamorphosed Jurassic sandstone and siltstone. Deposit consists of veins of quartz, quartz-feldspar, quartz-tourmaline and quartz-carbonate and altered zones of quartz, K-feldspar, sericite and albite. Veins and zones range from 1 to 50 m thick and have variable trends in plan view. Deposit is large and low grade and has no visible boundaries. Extent of deposit determined by geochemical sampling. Gold and Au-sulfides occur. Au deposit mineral assemblage is quartz-adularia-carbonate veins and the Au-sulfide is quartz veins with pyrite, galena, stibinite and Ag-sulfosalts. **References**: N.E. Malyamin and V.E. Bochkareva (written commun., 1990); V.N. Akatkin (written commun., 1991).			
52º 22’ N 115º 33’ E	Darasunskoye Russia Nerchinskiy	Au Granitoid-related Au vein	Grades ranges to a few to 300 ppm Au; average grade of 6.5 ppm Au.
Summary: Deposit consists of over 120 steeply-dipping quartz-sulfide veins that extend along strike for 1.0 to 1.2 km. Zone of veins ranges from 100 to 1,000 m thick and individual veins range from 5 to 20 cm thick. A zone of wallrock marginal to veins ranges from 0.6 to 1.5 m thick and contains disseminated sulfides. Main ore minerals are pyrite, arsenopyrite, chalcopyrite, pyrrhotite, galena, sphalerite, Pb, Cu, Ag, Bi, As, and Sb sulfosalts, tellurides, native gold, quartz, carbonates, and tourmaline. Principal economic gold-bearing mineral assemblages are: chalcopyrite-gray ore, chalcopyrite-pyrrhotite, pyrite-arsenopyrite, and sphalerite-galena. Gold occurs in arsenopyrite, pyrite, chalcopyrite, pyrrhotite, and gray ore, and is finely dispersed. Deposit occurs along the Mongol-Okhotsk and is hosted in mid- and Late Cretaceous K granodiorite-porphyry that intrudes a volcanic dome. **Reference**: Zvyagin and Sizikov (1971).			
48º 45’ N 106º 09’ E	Boroo Mongolia North Hentii 2	Au Granitoid-related Au vein	Average grade of 3.0 g/t Au. Resource of 40.0 tonnes Au.
Summary: Deposit is hosted by altered units of early Mesozoic gabbro, diabase, and diorite dikes. Deposit extends approximately 2.0 km along strike and ranges from 3 to 34 m thick. Ore mineral assemblages, from older to younger, are: pre-ore epidote-chlorite, quartz-sericite-albite-chlorite, gold-pyrite-arsenopyrite-K-feldspar-quartz, gold-beresite, quartz; gold-sulfide-quartz vein, and post ore calcite. Gold is fine-grained and occurs in pyrite and arsenopyrite, and as free gold in quartz veins. Main ore minerals are pyrite, arsenopyrite, sphalerite, chalcopyrite, galena, tetrahedrite, and gold. Main gangue minerals are quartz, sericite, Fe-carbonates, calcite, albite and muscovite. **References**: Blagonravov and Shabalovskii (1977); Dejidmaa (1985).			
53º 27’ N 126º 27’ E	Sanshandao, Shandong Province China Jiliaolu	Au Granitoid-related Au vein	Average grade of 6.13 g/t Au. Reserves of 59 tonnes Au.
Summary: Deposit consists of stockwork greater than 10 m thick, 1000 m long, several hundred meters deep down dip. Ore body is controlled by northeast-trending faults. Deposit minerals occur in a veinlet-stockwork and are composed of electrum, native gold, pyrite, galena, sphalerite, molybdenite and quartz and sericite. Host rock alterations are silica, sericite and pyrite and local K feldspar. Four deposition stages are: pyrite-quartz, quartz-fine pyrite, quartz-base metallic sulfides, and quartz-carbonates. Gold deposition temperature is about 350 to 230° C and is related to the Cretaceous granite (with a K-Ar isotopic age of 137 to 126 Ma). **Reference**: Liu (1990).			

Table 3. List of lode mineral-deposit models employed for metallogenic and tectonic analysis of Northeast Asia.

[Adapted from Obolenskiy and others (2003, this volume)]

Group	Type
Deposits related to mafic and ultramafic intrusions	Anorthosite Ti-Fe-P apatite
	Diamond-bearing kimberlite
	Mafic-ultramafic related Cu-Ni-PGE
	Mafic-ultramafic related Ti-Fe (±V)
	Podiform chromite
	Serpentinite-hosted asbestos
	Zoned mafic-ultramafic Cr-PGE
Deposits related to intermediate and felsic intrusions	Au skarn
	B (datolite) skarn
	Carbonate-hosted asbestos
	Cassiterite-sulfide-silicate vein and stockwork
	Co skarn
	Cu (±Fe, Au, Ag, Mo) skarn
	Fe skarn
	Felsic plutonic U-REE
	Fe-Zn skarn
	Fluorite greisen
	Granitoid-related Au vein
	Muscovite pegmatite
	Polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork
	Porphyry Au
	Porphyry Cu (±Au)
	Porphyry Cu-Mo (±Au, Ag)
	Porphyry Mo (±W, Bi)
	Porphyry Sn
	REE-Li pegmatite
	Sn skarn
	Sn-B (±Fe) skarn (ludwigite)
	Sn-W greisen, stockwork, and quartz vein
	Ta-Nb-REE alkaline metasomatite
	W±Mo±Be skarn
	W-Mo-Be greisen, stockwork, and quartz vein
	Zn-Pb(±Ag, Cu, W) skarn
Deposits related to alkaline intrusions	Albite syenite-related REE
	Alkaline complex-hosted Au
	Apatite carbonatite
	Charoite metasomatite
	Fe-REE carbonatite
	Fe-Ti (±Ta, Nb, Cu, apatite) carbonatite
	Magmatic and metasomatic apatite
	Magmatic graphite
	Magmatic nepheline
	Peralkaline granitoid-related Nb-Zr-REE
	Phlogopite carbonatite
	REE (±Ta, Nb, Fe) carbonatite
	Ta-Li ongonite

Table 3. List of lode mineral-deposit models employed for metallogenic and tectonic analysis of Northeast Asia.—Continued

[Adapted from Obolenskiy and others (2003, this volume)]

Group	Type
Deposits related to marine extrusive rocks	Besshi Cu-Zn-Ag massive sulfide Cyprus Cu-Zn massive sulfide Volcanogenic Cu-Zn massive sulfide (Urals type) Volcanogenic Zn-Pb-Cu massive sulfide (Kuroko, Altai types) Volcanogenic-hydrothermal-sedimentary Pb-Zn (±Cu) massive sulfide Volcanogenic-sedimentary Fe Volcanogenic-sedimentary Mn
Deposits related to subaerial extrusive rocks	Ag-Pb epithermal vein Ag-Sb vein Au-Ag epithermal vein Au-K metasomatite (Kuranakh type) Barite vein Basaltic native Cu (Lake Superior type) Be tuff Carbonate-hosted As-Au metasomatite Carbonate-hosted fluorspar Carbonate-hosted Hg-Sb Clastic sediment-hosted Hg±Sb Epithermal quartz-alunite Fluorspar vein Hg-Sb-W vein and stockwork Hydrothermal Iceland spar Hydrothermal-sedimentary fluorite Limonite Mn vein Ni-Co arsenide vein Polymetallic (Pb, Zn, Ag) carbonate-hosted metasomatite Polymetallic (Pb, Zn±Cu, Ba, Ag, Au) volcanic-hosted metasomatite Rhyolite-hosted Sn Silica-carbonate (listvenite) Hg Sulfur-sulfide (S, FeS2) Trap related Fe skarn (Angara-Ilim type) Volcanic-hosted Au-base-metal metasomatite Volcanic-hosted Hg Volcanic-hosted U Volcanic-hosted zeolite
Deposits related to hydrothermal-sedimentary sedimentary processes	Bedded barite Carbonate-hosted Pb-Zn (Mississippi Valley type) Chemical-sedimentary Fe-Mn Evaporate halite Evaporate sedimentary gypsum Korean Pb-Zn massive sulfide Polygenic REE-Fe-Nb deposits (Bayan-Obo type) Sedimentary bauxite Sedimentary celestite Sedimentary exhalative Pb-Zn (SEDEX) Sedimentary Fe-siderite Sedimentary Fe-V Sedimentary phosphate Sediment-hosted Cu Stratiform Zr (Algama Type)

Table 3. List of lode mineral-deposit models employed for metallogenic and tectonic analysis of Northeast Asia.—Continued

[Adapted from Obolenskiy and others (2003, this volume)]

Group	Type
Deposits related to metamorphic processes	Au in black shale
	Au in shear zone and quartz vein
	Banded iron formation (Algoma type)
	Banded iron formation (Superior type)
	Clastic-sediment-hosted Sb-Au
	Cu-Ag vein
	Homestake Au
	Metamorphic graphite
	Metamorphic sillimanite
	Phlogopite skarn
	Piezoquartz
	Rhodusite-asbestos
	Sedimentary-metamorphic borate
	Sedimentary-metamorphic magnesite
	Talc (magnesite) replacement
Deposits related to surficial processes	Bauxite (karst type)
	Laterite Ni
	Placer and paleoplacer Au
	Placer diamond
	Placer PGE
	Placer Sn
	Placer Ti-Zr
	REE and Fe oolite
	Weathering crust and karst phosphate
	Weathering crust Mn (±Fe)
	Weathering crust REE-Zr-Nb-Li carbonatite
Exotic deposits	Impact diamond